A borehole-to-surface electromagnetic survey

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Summary

We have assessed the feasibility of borehole to surface electromagnetic measurements for fluid injection monitoring. To do this we performed a vertical electromagnetic profiling (VEMP) experiment at the University of California Richmond Field Station where a saline water injection zone was created at a subsurface depth of 30 meters. The methodology used is quite similar to the conventional seismic (VSP) procedure for surface to borehole measurements. In our case however, the transmitter was located in a PVC cased borehole while the receivers were deployed on the surface. With a carefully designed system operating at 9.6 kHz we were able to make measurements accurate to 1% in amplitude and 1 degree in phase. The data profiles at surface were centered on the injection well and extended for 60 m on either side of it. Measurements were made at 5 m intervals. Although the VEMP process is quite vulnerable to near surface conductivity anomalies we readily detected the flat tabular target zone which was about 3 m thick and covered an area of about 120 m^2.

Introduction

Subsurface seismic measurements are now common practice either in the cross-borehole configuration or the surface to borehole (VSP) mode (Bregman et al., 1989, and Hatton et al., 1986). The acquired data provides good lithology information and in some cases porosity data. It can not, however, indicate the nature of the contained fluids and provides no information on their electrical conductivity. To obtain the subsurface distribution of this vital parameter we have embarked on a series of experiments in subsurface electromagnetics. The feasibility of such measurements was first demonstrated theoretically by Zhou et al. (1993) and experimentally by Wilt et al. (1994) in an oil field environment and by Alumbaugh et al. (1992) in a scaled down controlled field test. This previous work was entirely dedicated to the assessment of cross-borehole "EM diffusion tomography" where the measurements were analogous to seismic diffraction tomography.

Electromagnetic surface to borehole technology has been in common use in the mining industry in the search for steep ore deposits (Dyck 1991). Most commonly a powerful transmitter is placed on the surface while the receiver traverses the exploration borehole. Wilt and Ranganayaki (1990) adapted this technology to oil field use and demonstrated the feasibility of characterizing the subsurface with a large separation logging system. Here a multifrequency transmitter was deployed on surface and centered on the well collar while the receiver traversed the borehole. Building on this knowledge we perceived the possibility of mapping the subsurface resistivity distribution in the rather common circumstance where only one well is available for survey purposes. For logistic reasons, we elected to configure the measuring system with a plurality of receivers at surface which detect the electromagnetic fields of a transmitter that traverses the available borehole. Because the measuring technique is analogous to the conventional VSP method we have called it Vertical Electromagnetic Profiling or VEMP.

Equipment

The VEMP equipment is sketched in Figure 1. It includes a ferrite cored transmitter solenoid for downhole deployment and four surface detectors which can be set to measure either the vertical or the horizontal component of the transmitted electromagnetic fields. The transmitter was driven by an integral 9.6 kHz oscillator module which received DC power from surface. At a power level of about 140 watts, the transmitter had a magnetic moment of about 200 A-m^2. The four detectors were standard BF-6 induction magnetometers on loan from Electromagnetic Instruments Inc. of El Cerrito, CA. These sensors have a sensitivity of about 160 mV/nT at 9.6 kHz and an inherent noise level of about 2 $fT/\sqrt{Hz}$ at that frequency. The magnetic signals were then processed by a bank of EG&G model 5110 lock-in amplifiers set at 1/12 Hz bandwidth. The reference signal was derived from a flux monitor on the transmitter core and was linked to the receiving equipment via an optical fiber path. A separate link carried the transmitter pulley shafted encoder signals which triggered a digital data acquisition scan every 3 cm of the transmitter traverse. The survey borehole was traversed at a speed of about 1.2 m/min.

The accuracy of the measurements made with this equipment was demonstrated first with data acquisition repeatability tests and then, more critically, by reciprocity tests. The latter were done using two neighboring wells and a downhole receiver. In this case the measurements were repeated by physically interchanging these two system elements. The initial reciprocity tests indicated a serious electrical leak caused by a flaw in the electrical ground connections for the transmitter. At first this was remedied by locating the system ground point downhole. Subsequently however it was found that this leak was caused by capacitive coupling of the transmitter to the wellbore. It was remedied by balancing the transmitter circuit with respect to ground so that the ground point could once again be placed on the surface.

Once the grounding problem was attended to, the system noise proved to be about 16 $fT/\sqrt{Hz}$ at 9.6 kHz. This level is higher than the specific detector noise of about 8 $fT/\sqrt{Hz}$ but includes all hardware noise, industrial noise, and a component due to transmitter unit vibration. The observed noise was about 70 dB below the weakest signal levels. The required accuracy for the measurements of 1% in amplitude and 1 degree in phase was attained.

Data Acquisition

The UCB Richmond Field Station is located about 10 km north of the Berkeley Campus. Here, a 40 m layer of unconsolidated deltaic deposits covers a basement of sandstone and shale. The unconsolidated material is composed of intercalated layers of bay mud, clay, sand and occasional gravel. The mud and clay resistivity ranges from 5 to 20 ohm-m while the sand resistivity covers a 12 - 33 ohm-m range. The bedrock resistivity is greater than 100 ohm-m. The injection well was placed so that it intersected a 3 m thick gravel layer that was located immediately above the bedrock. The saline target zone used in this controlled experiment was created in the gravel layer by injecting 210,000 liters of saline water whose electrical resistivity was 1 ohm-m. Measurements were made after injection and after the complete extraction of the saline target.

A plan of the test site is shown in Figure 2. Measurements of the vertical and the horizontal components of the transmitted 9.6 kHz magnetic fields were made along two intersecting, 120 m long, profiles, which were centered on the injection well. The station interval was 5 m. Pre and post extraction as well as measurements difference of the two measurements is shown in Figure 3. Here we display the amplitude of the vertical component of the measured magnetic field in units of dB below 1 nA/m normalized to a transmitter moment of 1 A-m^2. In these units a 1 dB change corresponds to about 12% of signal strength variation. Although the presence of the injection zone is not overly apparent in the raw data shown in parts (a) and (b) of the illustration, its presence is clearly indicated in the phasor amplitude difference plot (Figure 3(c)). It is clearly outlined by the two horizontal anomalies at the 30 m level. The minor asymmetry in the residual field amplitude pattern indicates an eccentric target zone displaced slightly toward the drillhole EMNW. We were initially perplexed by the vertical anomaly features one of which was centered by the transmitter well position (-5m) while the other appeared at the NW extremity of the profile. Subsequent investigation revealed that these were related to very near surface metallic debris and could be ignored in the interpretation process.

Preliminary Data Interpretation

No detailed inversion of the measurements is presently available as the technique for doing this is under development. We were able however to estimate the parameters of the target zone with forward modeling. To do this we used the SHEETS algorithm described by Zhou (1989). After some trial and error we arrived at a 10x12 m flat tabular body with an estimated thickness of 3 m and a conductance of 1 S/m. A projection of this feature is shown on the survey area plan in Figure 2. The simulated residual data for this model are shown in Figure 3(d). While there are evident differences between these two sets of results, there is good qualitative agreement that is indicative of the utility of the new technology.

Conclusions

We have demonstrated that satisfactory VEMP data can be routinely acquired with properly functioning equipment. Great care however must be taken to identify and remove the effects of any surficial material. Much work is to be done to develop robust and efficient inversion method for VEMP measurements. Once this is done we expect this technology to play an significant role in oil reservoir characterization and environmental remediation.

References

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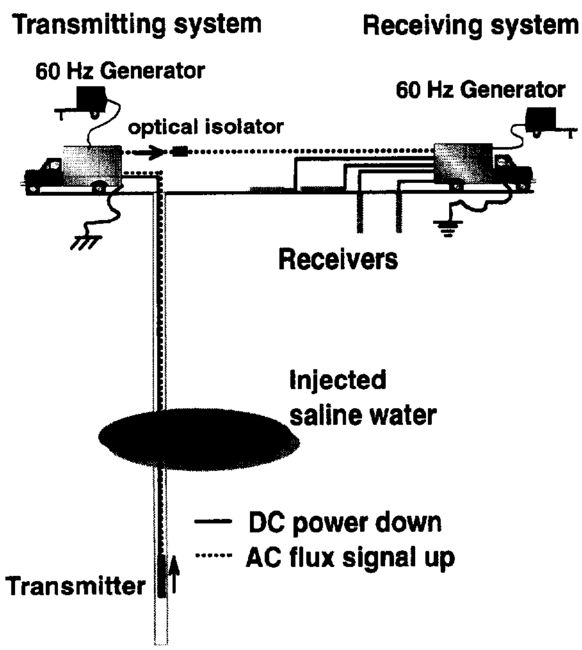


Fig. 1 Field layout of the data acquisition system.

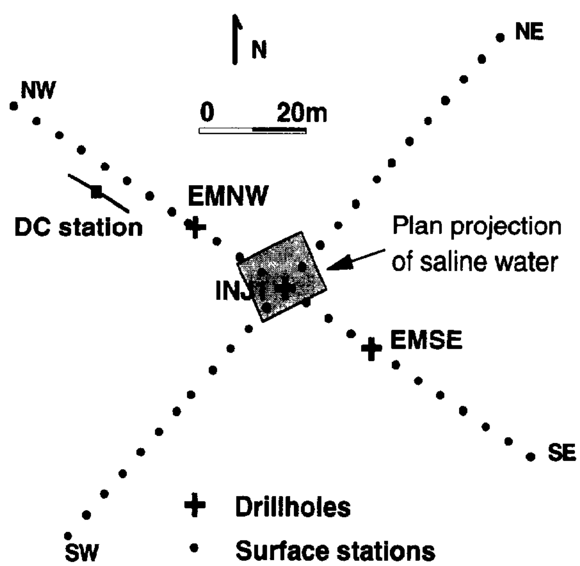


Fig.2 Well map at the Richmond Field Station.

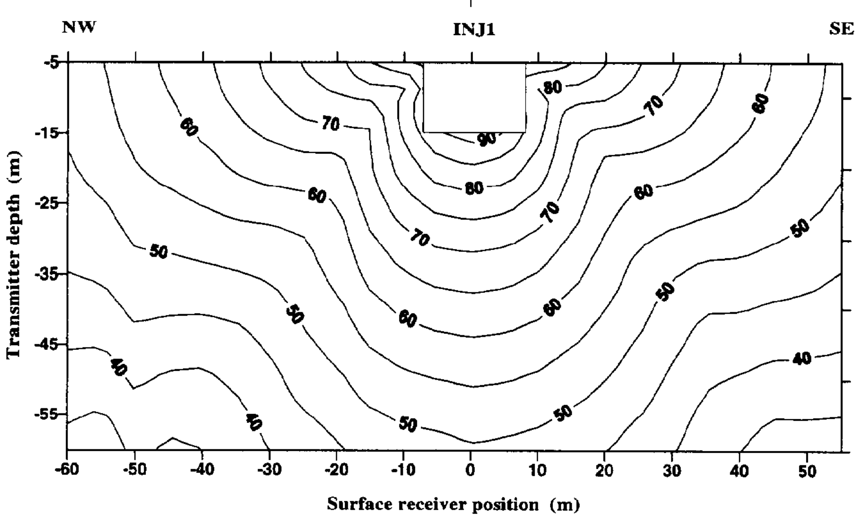


Fig. 3(a) Vertical total field amplitude in dB relative to 1 nA/m, pre-extraction data.

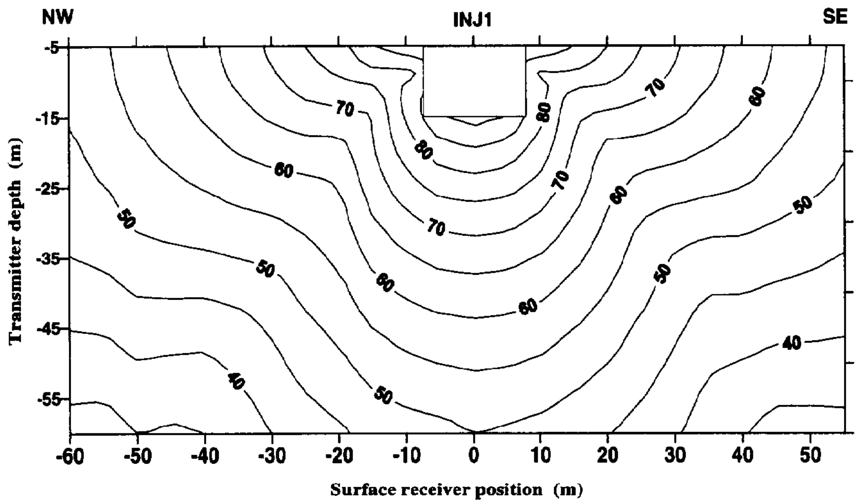


Fig. 3(b) Vertical total field amplitude in dB relative to 1 nA/m, post-extration data.

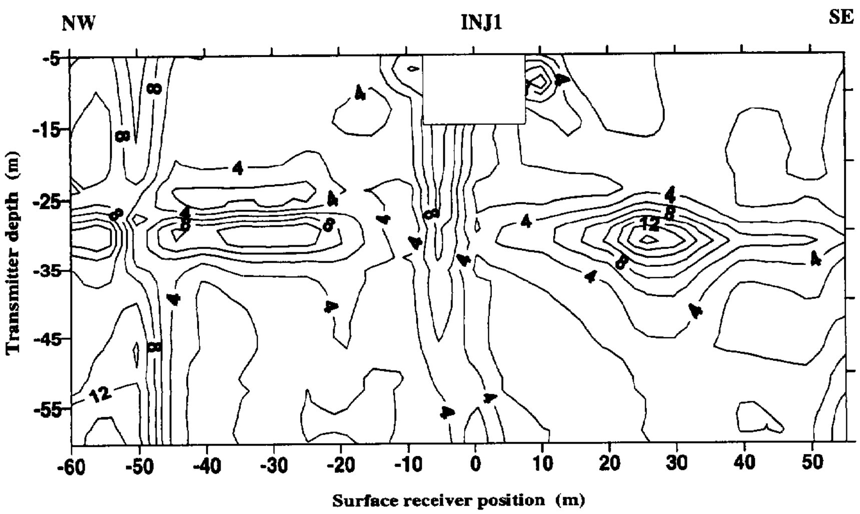


Fig. 3(c) Vertical secondary field amplitude as a percentage of the background field.

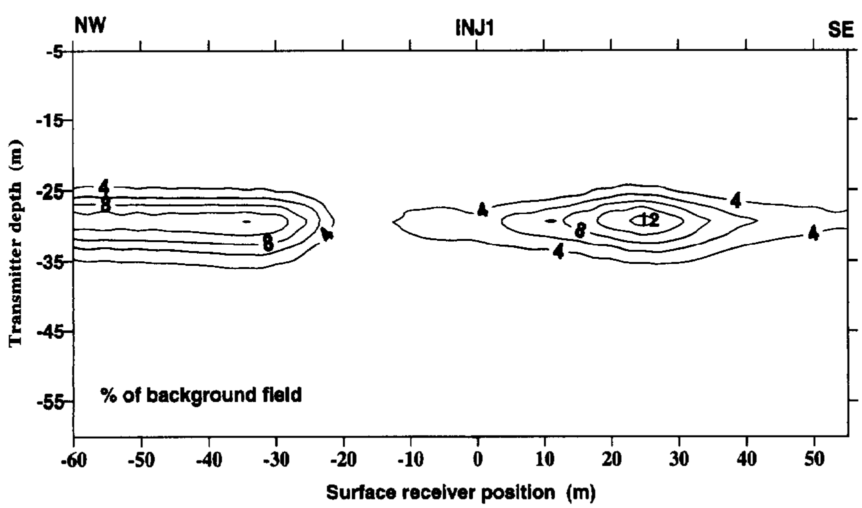
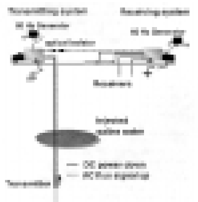


Fig. 3(d) Numerical values for the vertical secondary field of the tabular model.


Transmitting system
Receiving system
Receivers
Injected
saline water
DC power lines
Transmitter